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APPLICATION OF LINEAR RESPONSE THEORY TO EXPERIMENTAL DATA OF SIMULTANEOUS RADIATION AND ANNEALING RESPONSE OF A CMOS DEVICE

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This report deals with an application of linear response theory to experimental data of simultaneous radiation and annealing response of a CMOS device. In particular, we apply the method we have developed earlier to determine the characteristic time, t_o, as well as the parameters A and C in the ln(t) dependence of the linear response function R(t):

$$R(t) = -C + A\ln(1-t/t_o). \tag{1}$$

Our method is based on a study of the linear response for $t \ll t_o$, when R(t) can be expanded in a power series of t:

$$R(t) = R(0) + R'(0)t + 1/2R''(0)t^2 + 1/3R'''(0)t^3 + \ldots \tag{2}$$

where R'(0) and R"(0) are, respectively, the first and second derivatives of R with respect to t. At the point t=0, R(0) is R(t=0).

To find the linear response, one needs to substitute R(t-t') in the form of Eq.(2) into our general equation for the shift of the threshold potential:

$$\delta V(t) = \dot{D}\int_0^t R(t-t')dt', \tag{3}$$

where $\dot{D}$ is the dose rate (here considered to be constant). Substituting Eq.(2) into Eq.(3), we obtain

$$\delta V(t) = \dot{D}R(0)\int_0^t dt' + \dot{D}R'(0)\int_0^t (t-t')dt' +$$

$$+ 1/2\dot{D}R''(0)\int_0^t (t-t')^2 dt' + 1/3\dot{D}R'''(0)\int_0^t (t-t')^3 dt' + \ldots \tag{4}$$

Integrating, we obtain

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$$\delta V(t) = D_{tot}[R(0) + 1/2R'(0)t - 1/6R''(0)t^2\} - 1/24R'''(0)t^3, \quad (5)$$

where $D_{tot} = D(t) = \dot{D}t$.

In particular, for the ln(t) dependence,

$$R(t) \approx -C + A(t/t_o) - 1/2A(t/t_o)^2, \quad (6)$$

or, comparing Eq.(6) and Eq.(3),

$$R(0) = -C,\ R'(0) = A/t_o,\ R''(0) = -A/t_o^2 \text{ and } R'''(0) = 2A/t_o^3. \quad (7)$$

We obtain the following expression for the shift of threshold potential by substituting Eq.(7) into Eq.(5):

$$\delta V(t) = D_{tot}[-C + 1/2A(t/t_o) - 1/6A(t/t_o)^2 - 1/12A(t/t_o)^3], \quad (8)$$

where $t \ll t_o$.

It is more convenient to deal with the shift per unit dose:

$$\delta V(t)/D_{tot} = a_o + a_1 t + a_2 t^2, \quad (9)$$

where the constants are

$$a_o = -C,\ a_1 = A/2t_o,\ a_2 = -A/6t_o^2. \quad (10)$$

For the general case, we have

$$a_o = R(0),\ a_1 = 1/2R'(0),\ a_2 = -1/6R''(0). \quad (10a)$$

To test our method, we planned and participated in irradiation experiments conducted on RCA 10^6 rad-hard CMOS ICs at the Goddard Space Flight Center Radiation Facility. We chose a dose rate equal to approximately 130 rads/min. An IC was irradiated with ^{60}Co gamma rays for several hours, taking measurements of the threshold potential (evaluated at a drain current of 300 µA) for one n-channel and one p-channel transistor every ten minutes.

One can expect a linear dependence of $\delta V(t)/D_{tot}$ for small times when

$$a_2 t^2/a_1 t = t/2t_o \ll 1, \quad (11)$$

or

$$t \ll t_o/3.$$

The first three points showed the linear dependence of $\delta V(t)/d_{tot}$ (30 min.) in both cases, but the fourth point deviated from that dependence. From this, we could conclude at once that $t_o \gg 3t$ = 30 min. In other words, that t_o was between one and two hours. We used the linear part of the curves (the first 2-3 points) to find a_o and a_1, and we then used the next part of the curve to find a_2. The constants a_1 and a_2 allowed us to calculate t_0 and A:

$$t_0 = -1/3\ a_1/a_2$$

$$A = -2/3\ a_1^2/a_2. \tag{12}$$

For the p-channel transistor, we found t_0 to be approximately 110 min. and for the n-channel, $t_0 \approx 70$ min.

For the p-channel, the theoretical curve,

$$\delta V(t)/D_{tot} = a_0 + a_1 t + a_2 t^2,$$

deviates from the experimental points only after 70 min., which is $0.64t_0$, and for the n-channel, the deviation takes place after 45 min., which is also $0.64t_0$.

For the n-channel, we then plotted a more precise theoretical curve, adding one more term, $a_3 t^3$:

$$\delta V(t)/D_{tot} = a_0 + a_1 t + a_2 t^2 + a_3 t^3.$$

The value of a_3 was found from Eq.(10) and (10a):

$$a_3 = 3/2\ a_2^2/a_1 = 0.00196 \approx 0.002. \tag{13}$$

We plotted this improved curve to t = one hour, which gives $t/t_0 = 0.86$. There is no point in continuing the curve further, since the condition $t/t_0 \leq 1$ must hold and the expansion (Eq.(6)) is definitely not valid beyond this point. In any event, our purpose was to analyze the region $t/t_0 \leq 1$.

It is worth noting that our lack of data on the dependence of R(t) on dose rate and temperature at this point prevents development of the microscopic (quantum) theory of annealing.

If we find that, in some cases, R(t) does not possess a ln(t) dependence (Eq.(1)), our method still allows us to find the value of R(t) and its derivatives at t = 0 through Eq.(5). Again, by conducting experiments for different dose rates (or temperatures), one can obtain the dependence of R(0), R'(0) and R'"(0) on these variables. Since R'(0) is proportional to $1/t_0$ and R"(0) is proportional to $1/t_0^2$, we can determine the dependence of t_0 on temperature or dose rate.

The case of pure annealing can be treated in the same way. Instead of Eq.(3), we will use our general equation:

$$\delta V(t) = \dot{D}\int_0^{t_r} R(t-t')dt'. \tag{14}$$

Substituting Eq.(2) in Eq.(14), we obtain

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$$\delta V = D_{tot}[R(0) + R'(0)(t - 1/2t_r) + + 1/2R''(0)(t^2 - tt_r - 1/3t_r^2) + +1/3R'''(0)(t^3 - 3t^2t_r + tt_r^2 - 1/4t_r^3)] \quad (15)$$

or

$$\delta V(t)/D_{tot} = R(0) - 1/2R'(0)t_r - 1/6R''(0)t_r^2 - 1/12R'''(0)t_r^3 + [R'(0) - 1/2R''(0)t_r + R'''(0)t_r^2]t + (1/2RR''(0) - 1/2R'''(0)t_r)t^2 + 1/3R'''(0)t^3. \quad (16)$$

Since we are concerned with the case $t_r/t_o << 1$, Eq.(16) can be simplified:

$$\delta V(t)/D_{tot} = R(0) + R'(0)t + 1/2R''(0)t^2 + 1/3R'''(0)t^3. \quad (17)$$

In particular, for the ln(t) dependence, we substitute Eq.(7) into Eq.(17) and obtain

$$\delta V(t)/D_{tot} = -C + A(t/t_o) -1/2A(t/t_o)^2 + 2/3A(t/t_o)^3 \quad (18)$$

Then, as in the case of simultaneous irradiation and annealing, we can, in principle, determine a_o, a_1 and a_2 from experimental data. We can then calculate t_o and A:

$$t_o = -1/2\ a_1/a_2$$

$$A = -1/2\ a_1^2/a_2$$

$$C = -a_o. \quad (19)$$

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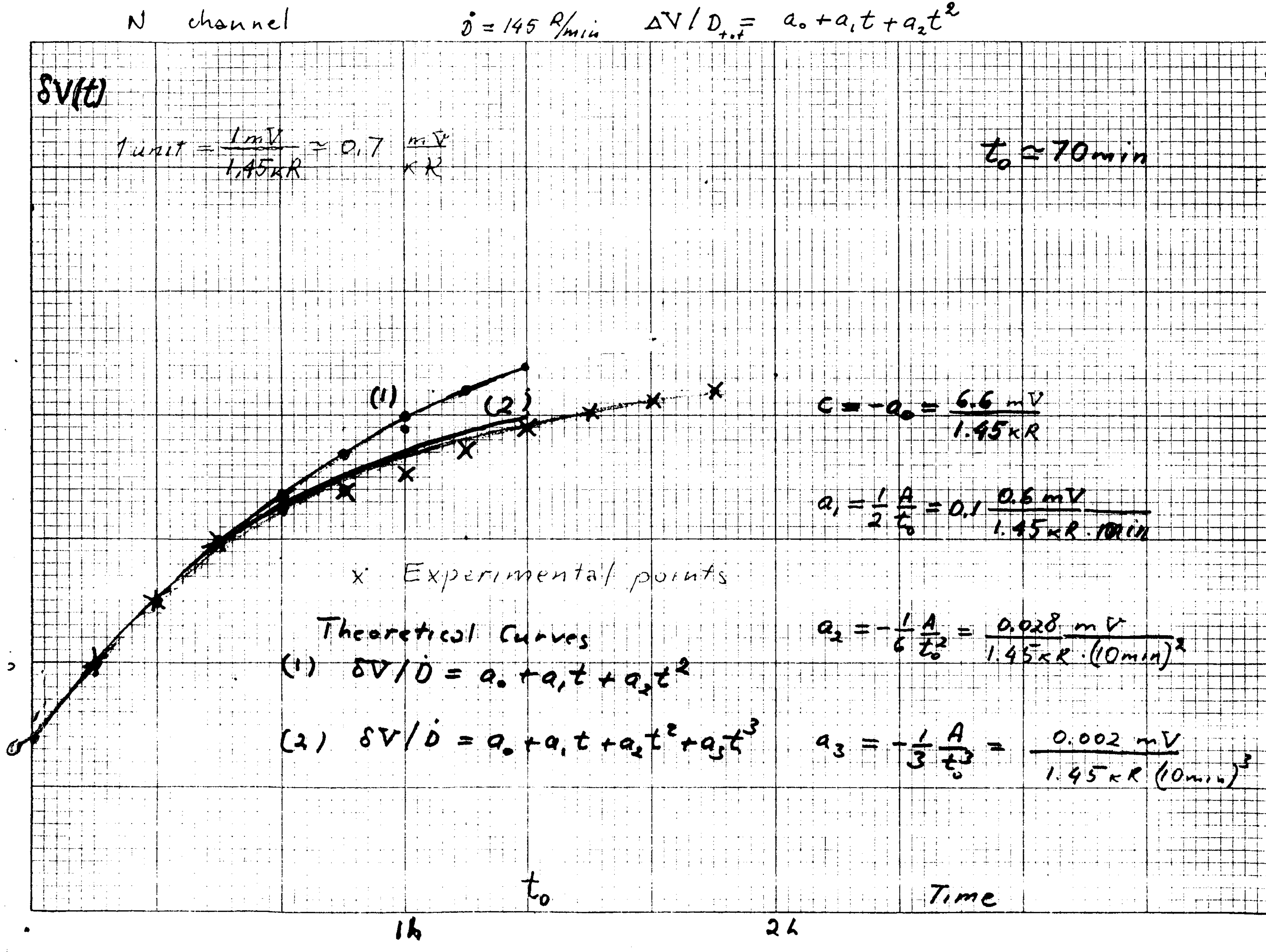

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